

Intermediate-Depth Circulation in the Gulf of Mexico Estimated from Direct Measurements

Georges L. Weatherly¹, Nicolas Wienders¹, and Anastasia Romanou²

¹Department of Oceanography
Florida State University
Tallahassee, FL 32306-4320 USA

²Department of Applied Physics and Applied Mathematics
Columbia, University
New York, NY 10025 USA

Data from 17 PALACE floats set in the Gulf of Mexico sampling the intermediate-depth (≈ 900 dbar) flow from April 1998 to February 2002 indicate a mean cyclonic circulation along the northern and western edges of the Gulf of Mexico. This flow intensified into a ≈ 0.10 m/s current in the western Bay of Campeche and was deflected around a topographic feature, called here the Campeche Bay Bump, in the southern Bay of Campeche. Floats launched in the eastern Gulf of Mexico tended to stay there, and those launched in the western Gulf tended to stay in the western Gulf, suggesting restricted connection at depth between the eastern and western Gulf of Mexico. Not surprisingly, the measured flow was stronger when the measured flow was under the Loop Current and warm-core rings, but the direction of the intermediated depth currents bore no apparent relation to the surface flow inferred from satellite altimeter maps. However, comparing the floats' surface drifts to their intermediate depth drifts, the floats at depth ended to track the surface flow in the Loop Current, and both indicate a cyclonic gyre in the Bay of Campeche.

1. INTRODUCTION

This is a report of inferred intermediate depth circulation in the Gulf of Mexico obtained from 17 PALACE (Profiling Autonomous Lagrangian Circulation Explorer) floats [Davis *et al.*, 2001]. The floats were acquired and set by John Blaha of the Naval Oceanographic Office, Stennis Space Center, MS, as part of a National Oceanographic Partners Program study of the

Gulf of Mexico [Blaha *et al.*, 2000]. The authors of this report were invited to examine the PALACE data after the floats were set.

PALACE floats are a relatively new instrument for inferring intermediate depth flow. They were first used for this purpose in the Drake Passage [Davis *et al.* 1992]. More recently they have been used in studies in the tropical and south Pacific [Davis, 1998], in the northern Atlantic, e.g., Lavender *et al.* [2000] and western tropical Atlantic [Kwon and Riser, 2005], in the southwestern Indian Ocean, e.g., Chapman *et al.* [2004], in the Southern Oceans [Gille, 2003], in the Bering Sea [Johnson *et al.* 2004], and in the Okhotsk Sea [Oshinin *et al.* 2004]. The floats are not tracked as they drift at depth as the SOFAR (SOund Fixing And Ranging) and RAFOS (SOFAR spelled backwards) floats are: see, for example, Owens [1991] and Richardson and Garzoli [2003]. Instead they are tracked at the surface by satellite shortly before they descend to the drift depth and, after drifting at depth for a fixed interval, which ranged in the studies above from about four to twenty-five days, they are tracked again after they surface. It is these surface fixes which are used to estimate the intermediated-depth drift.

In the above PALACE studies of Davis *et al.* [1992], Davis [1998], Lavender *et al.* [2000], and Gille, [2003], the floats were at the surface for about 21 hours. This relatively long time was chosen so that enough surface fixes could be obtained so that the surface drift would be objectively extrapolated to the times the float surfaced and submerged. Then the start and stop location of each intermediate-depth drift was estimated assuming a geostrophic shear and knowing the time it takes the float to sink and to rise. The technique is quite involved [Davis *et al.*, 1992] and requires the surface drift time be longer than the inertial period. With a surface fix error of ± 2 km and submerged time of 25 days Davis [1998] estimates an error of ± 0.001 m/s in the intermediate depth drift.

In some cases, such as this study, where the study region is semi-enclosed such as the Bering Sea [Johnson *et al.* 2004], and the Okhotsk Sea [Oshinin *et al.* 2004] or in regions of topography such as the western Labrador Sea [Fischer and Schott, 2002] and the western, tropical Atlantic [Kwon and Riser, 2005], a shorter surface time of about 12 hours is chosen to reduce the risk that the floats drift into water shallower than their programmed drift depths while at the surface. Johnson *et al.* [2004] Kwon and Riser [2005], and Oshinin *et al.* [2004] assumed that the last surface fix before submerging is a reasonable estimate of the beginning location of the intermediate depth drift, and the first surface fix after resurfacing is a reasonable estimate of the end location of the intermediate level drift. They estimate that this introduces an error of about 10% in their intermediate depth drifts. Fischer and Schott [2002] did carefully, hand-edited polynomial fits to the surface fixes and extrapolation to estimate the float positions when they

surfaced and their positions when they sank. With a surface fix error of ± 0.5 km and submerged time of 5 or 10 days they estimate an uncertainty of ~ 0.01 m/s in the intermediate depth drifts.

The floats examined here drifted at ≈ 900 dbar for 6.23 days and surfaced for 11.5 h once every week. They were launched in the northern Gulf of Mexico (the launch coordinates and dates are given in *Weatherly* 2004), but drifted throughout the Gulf of Mexico (Plate 1). The flow in much of the open Gulf of Mexico, here taken to be in water deeper than the ≈ 900 m of the floats' drift depth, is dominated by the Loop Current and Loop Current rings in the eastern Gulf and Loop Current rings elsewhere (e.g., *Schmitz* [this issue]), Loop Current rings here meaning cyclonic rings as well as the more familiar anticyclonic ones. Since these features extend down to about the drift depth of the floats (e.g., *ibid.*), the floats should at times respond to these features if below them. Though the floats drifted throughout the Gulf of Mexico, the majority of the intermediate-depth drifts were from the lower continental margin (Plate 1). The lower continental margin is a region of energetic topographic Rossby waves [*Hamilton and Lugo-Fernandez*, 2002, *Oey and Lee*, 2003]. Therefore the floats drifted in regions rich with transient, strong currents with time scales \approx a month.

The data which these floats yielded over a four-year period beginning in April 1998 (Figure 1) make possible long-term mean circulation estimates in water deeper than ≈ 900 m. The floats drift depth is near the transition depth for an upper layer and lower layer flow regimes. We now review some of what is thought to occur in each regime. Drifter observations obtained over a ten-year interval indicate an anticyclonic basin-wide, excluding the Bay of Campeche (the bay in the southwestern Gulf), surface-flow pattern [*DiMarco et al.* this issue] although in the northern Gulf along the continental margin this flow is weak and ill defined. These data also indicate that in the winter this gyre may split into an eastern one and a western one at about 88°W . An average of a nine-year numerical simulation, shown in *Lee and Mellor* [2003], shows a basin-wide anticyclonic flow pattern near the surface. At about 1000 m depth this and two other numerical studies [personal communication by *Welsh* [2002] and Groupment Mercator] indicate a weaker basin-wide cyclonic flow pattern in the Gulf of Mexico. Consistent with a 1000-m depth cyclonic flow pattern are the mean current records of duration ≥ 1 year from the northern and eastern Gulf [*Hamilton*, this issue]. *DeHaan* [2003], using historic hydrographic and current meter data presented in *Hamilton* [1990], also inferred a deep cyclonic flow. In the Bay of Campeche *Vazquez de la Cerda* [1993] and *Vazquez de la Cerda et al.* [this issue] describe a quasi-permanent upper layer cyclonic gyre in the Bay of Campeche which they inferred was wind driven. The drifter data reported in *DiMarco et al.* [this issue] also indicate a cyclonic gyre in this Bay. *Vazquez de la Cerda et al.* [this issue] infer using results presented in this study that

this cyclonic flow extends down to ≈ 1000 -m depth. No western intensification of the surface flow is apparent in the Bay of Campeche [Vazquez de la Cerda, 1993, Vazquez de la Cerda et al., this issue, DiMarco et al., this issue].

2. DATA AND DEEP DRIFT ESTIMATES

The floats were set to drift at 800 dbar so the temperature profiles they made as they surfaced each week complemented those made by 800-m XBTs [personal communication, Sturges, 2002]. Their drift depths varied from 830 dbar to 1040 dbar, with the mean depth near 900 dbar [Weatherly, 2004]. Their drift depths increased with time at a rate about $23 \text{ dbar/yr} \pm 10 \text{ m/yr}$. Some of the floats drifted over three year, so that towards the end some were drifting at depths about 100 dbar deeper than when they started. In this study we refer to their drift depth collectively as 900 dbar. The geostrophic shear in the depth range in which the floats drifted is weak [DeHaan, 2003].

About 30% of the Gulf of Mexico is shallower than 900 m, and even with a relatively short surface time (11.5 hours every 7 days), it was not unusual for a float while at the surface to drift into water shallower than the drift depth (Plate 1, the trajectories shoreward of the 900 m isobath). All float trajectories which had a depth < 830 dbar, the minimum of the initial depths to which the floats descended, were assumed to be grounded, and were excluded. As many of the trajectories were along the continental margin, the depth versus time plots of the floats were also examined for suspiciously shallow values, i.e., values > 830 dbar but notably shallower than their neighbors. If such values occurred adjacent to the 900 m isobath in Plate 1 they were considered grounded and also excluded. We obtained 1315 intermediated depth drifts.

The challenge with PALACE floats is to estimate the location at the beginning and end of each intermediate depth drift from surface fixes. The method we used to estimate the start and stop locations is somewhat between that used in Johnson et al. [2004], Oshinin et al. [2004], and Kwon and Riser, [2005], who assume the former is the last surface fix before submerging and the latter is the first fix after surfacing, and that used by Fischer and Schott [2002], who assume the former is the surface location at the time of sinking and the latter is the surface location at the time of first surfacing. As noted earlier Fischer and Schott [2002] used hand-edited polynomial fits of the surface fixes to extrapolate these locations. Here we estimated diving and surfacing positions by making linear extrapolations based on the first and last fix each time the float surfaced. To estimate the time at which the floats surfaced and sank we used a rise time of 2.5 h and a drift time at the surface of 11.5 h; to estimate when they reached drift depth we used a

sinking time of 4.5 h. These times were provided by the manufacturer of the floats, Webb Research, Falmouth MA USA.

Three to six satellite fixes were usually made at the surface, and we plotted all surface drifts based on these positions. These surface drifts look very much like those seen in Plate 1 which are based on the first and last fixes. Because there was some curvature in the drifts we re-estimated the sinking and rising positions on the basis of linear extrapolations on the two nearest fixes (the first two for the surfacing position and the last two for the dive position). The resulting intermediate-depth drifts are essentially the same as those presented here, and the conclusions presented here about the intermediate depth circulation do not change.

In the estimates of intermediate-depth drifts presented here we have attempted to remove the sub-surface drift which resulted when floats descended to their drift depth from the surface as well as that which occurred when they rose from drift depth to the surface. To do so we assumed that there was a linear decrease from the surface current (estimated from the surface fixes) to the current at the drift depth. We first estimated the location where the float reached drift depth and its location where it began to surface by assuming the current at the intermediate depth was zero. The intermediate depth drift was then estimated. Using that estimate, the drift during sinking and rising were then re-estimated. The procedure was repeated three more times. The deep-drift estimates essentially did not change after the second iteration, and the first estimate was generally within 10% of the final estimate. We also estimated the deep drifts assuming there was zero drift while sinking and rising and got essentially the same flow results.

The temperature-profile data returned by the floats is considered in *Weatherly et al.* [2003] and *Weatherly* [2004]. They are briefly considered here. The floats measured temperature every 10 dbar (5 dbar) for depths $>$ ($<$) 100 dbar while rising to the surface.

3. RESULTS

3.1 Intermediate-Depth Circulation

The intermediate-depth drift estimates are seen in Plate 1. In this paper we focus on the intermediate-depth velocities estimated from them and center these vectors at the mid-point of intermediate-depth drifts. These velocity estimates are shown in Figure 1, and are distinguished according to where the floats were launched. The darker (lighter) vectors are from floats launched west (east) of 88° W. There is a tendency for the floats launched in the eastern (western) Gulf of Mexico to remain in the eastern (western) Gulf of Mexico. It is interesting that the results of some numerical models tracking particles set to drift at 1000 m depth show little

communication between the eastern and western Gulf of Mexico (S. Welsh, 2002 personal communication). Also, we noted earlier that at the surface at least in the winter there may limited communication between the eastern and western Gulf (*DiMarco et al.*, this issue).

There are patterns in Figure 1, still more evident in Plate 2, which shows the same data averaged in 0.5° latitude by 0.5° longitude bins every $\frac{1}{4}^\circ$ latitude by $\frac{1}{4}^\circ$ longitude. Before noting them, we point out a topographic feature in Figure 1 which bears upon one of these patterns. In the southern Bay of Campeche the 2000 m isobath diverts away from the coast and 900 m isobath. Following *Brooks and Bane* [1978], who noted that the Gulf Stream was diverted around a topographic feature which they called the Charleston Bump, we hereafter refer to this feature as the Campeche Bay Bump. These flow features are:

- a tendency for cyclonic flow ≈ 0.05 m/s along the continental margin of the Gulf of Mexico
- an intensification of the above cyclonic flow to ≈ 0.10 m/s in the western Bay of Campeche
- a tendency for the flow in the southern Bay of Campeche to be diverted around the Campeche Bay Bump
- a cyclonic gyre in the western Bay of Campeche centered at 20.5°N , 95.5°W .

Plotting only those velocities in Plate 2 formed from averages when the number of samples $n \geq 5$ deletes many of the larger velocities (Figure 2). The above noted patterns survive in Figure 2.

Assuming the measurement errors are negligible (which is discussed later) the uncertainty in the velocity values in Figure 2 can be estimated from their variances using methods outlined in *Emery and Thompson* [2001]. For these estimates we assumed the integral time scale of the velocity fluctuations was 10 days; i.e., velocity measurements made 20 days apart were statistically independent. *Davis* [2004] made similar calculations for float data from the Pacific Ocean using a comparable integral time scale. Generally, if $n \geq 5$, the flow direction appears resolved in the western Gulf of Mexico and about the Campeche Bay Bump, but it is only marginally resolved elsewhere (Figure 4).

To estimate when the above-noted flow features were sampled during the \approx four-year duration study period, the intermediate-depth velocities were plotted for sequential six-month periods. These figures are shown in *Weatherly* [2004] and in this issue's CD; they are summarized in the table. The southerly flow along the western edge of the Gulf of Mexico, the intensified southerly flow along the western boundary of Bay of Campeche, and the cyclonic flow about the Campeche Bay Bump were sampled during much of the study period.

3.2 Variability

To see whether some of the velocities were related to intermediate-depth extensions of the Loop Current and Loop Current rings, we superposed the current vectors onto satellite altimeter maps. We tried two variants: monthly satellite maps with all currents within two weeks of the map and biweekly satellite maps with all currents within a week of the map. At times the intermediate-depth flow under the Loop Current and its rings appeared to extend to intermediate depth; at other times it did not (some examples of each are found in *Weatherly* [2004]). We could not tell ahead of time what to expect. For example, we could find no pattern if we considered only the Loop Current, newly formed Loop Current rings, or older rings.

There is some uncertainty with the float data and the satellite altimeter maps. To see if we could get more consistent results we restricted ourselves to velocity measurements made when both the temperature data from the float and the altimeter map indicated that the float had been under the Loop Current or an anticyclonic, warm-core Loop Current ring. As an example, Figure 4 shows all temperature profiles made from the 1° latitude by 1° longitude box centered at 22.5°N , 79.0°W . The profile farthest to the right is conspicuously warm indicating that this profile was made either in the Loop Current or a Loop-Current ring. Comparing the location of this profile (22.2°N , 77.9°W) with a satellite altimeter map for the date of this profile (25 November 1999) found at http://ww-ccar.colorado.edu/~realtime/gom/gom_nrt.html indicated that this profile was made in a Loop Current warm-core ring.

We found 103 cases in which a float's temperature profile and the associated altimeter map for the appropriate day indicated that the float was in the Loop Current or in a warm-core Loop Current ring. For these cases the intermediate-depth flow was stronger (Figure 5). However, we could discern no consistent pattern between the flow direction at intermediate depth and that indicated at the surface in the altimeter maps (not shown).

4. SUMMARY AND DISCUSSION

During the \approx four-year period during which the floats drifted, the average intermediate (900 dbar) depth flow was generally cyclonic along the continental margins in the northern and western portions of the Gulf of Mexico. There was too little data from the eastern and southern Gulf of Mexico to say whether this pattern extends to these regions. This flow strengthened to \approx

0.1 m/s in the western Bay of Campeche and was diverted around the Campeche Bay Bump in the southern Bay of Campeche.

The above results are not overly sensitive to the manner in which we estimated the intermediate depth drifts from the surface fixes. Taking last and first surface fixes as reasonable estimates of the start and end intermediate depth drift locations (as do *Johnson et al.* [2004], *Kwon and Riser*, [2005], and *Oshinin et al.* [2004]) gave the same flow pattern as in Figure 2 except that the current magnitudes were increased by about 10%. The latter is consistent with the 10% error reported with this assumption (*Johnson et al.* 2005). We tried two linear extrapolation methods to estimate the surface locations of surfacing and sinking and got essentially the same intermediate depth drift results for each. We did do polynomial fits to the to the surface drift fixes for two floats to estimate surfacing and sinking locations for these floats. We found, similarly to what *Fischer and Schott* [2004] found, that extensive editing was required to yield reasonable results. Most of the editing was automated (e.g., to exclude fixes separated in time by less than an hour) but other were done by hand (e.g., when the first surface fix was obtained five or so hours after surfacing). Because the intermediate depth drift for these two floats were nearly identical to those estimated earlier, and because the majority of the surface drifts were nearly linear we do not think the results we present would change appreciably if we had estimated sinking and surfacing locations by polynomial fits to the surface fixes.

In our estimated drifts we attempted to correct for possible drift while sinking from the surface to drift depth and while rising from drift depth to the surface. However, neglecting such drift (i.e., assuming the float went straight down and up) we got essentially the same flow pattern as in Figure 2 and essentially the same velocity histogram as in Figure 5 (solid curve) except the average value increased by 0.015 m/s.

We found that the conclusions of southerly flow along the western edge of the Gulf of Mexico and the diversion of the flow about the Campeche Bay Bump in Figure 2 were statistically significant. While the westerly flow along the northern edge of the Gulf of Mexico was marginally significant it was consistent with long-term moored current measurements from this region [*Hamilton*, this issue]. We attempted to account for some of the uncertainty in the intermediate- depth drift estimates resulting from an ± 1 km uncertainty in the surface fixes (this is intermediate to the ± 2 km uncertainty of *Davis*, [1998] and the ± 0.5 km uncertainty of *Fischer and Schott* [2002]). We found that the estimates are meaningless for inferred intermediate-depth velocities < 0.01 m/s, and for velocities ≈ 0.01 m/s, ≈ 0.05 m/s, ≈ 0.10 m/s the flow direction is resolved to $\approx \pm 45^\circ$, $\pm 13^\circ$, $\pm 7^\circ$, respectively. We excluded from the averages shown in Figure 2 all those with inferred intermediate depth currents ≤ 0.01 m/s and got again

the same flow pattern shown in Figure 2. Thus the conclusion of statistically significant southerly flow along the western edge of the Gulf of Mexico and diversion of this flow about the Campeche Bay Bump and marginally statistically significant westward flow along the northern edge of the Gulf of Mexico survives when the uncertainties in the surface fixes are included.

We found southward flow in the western Gulf to intensify in the Bay of Campeche. We are aware of only one numerical model [*Groupement Mercator*] which indicates an intensified southerly flow there (Figure 6). Although the 900-m and 2000-m isobaths converge around 20°-21°N in this region (Figure 1), the flow appears to intensify further upstream around 22°N both in the data (Figures 1 and 2) and in the Mercator simulation (Figure 6). The quasi-permanent wind-driven surface cyclonic gyre in the Bay of Campeche [*Vazquez de la Cerda* [1993], *Vazquez de la Cerda et al.* [this issue], *DiMarco et al.* [this issue]] is not westward intensified while the intermediate depth cyclonic gyre is. This may indicate the latter is associated with some as yet unidentified thermohaline or eddy-driven abyssal flow in the Gulf.

The Mercator model (Figure 6) also indicates a cyclonic gyre in the southwestern Bay of Campeche near the one previously noted one in the float data (Figure 2), although the latter is only marginally statistically significant (Figure 4). The Mercator model is also the only one we are aware of that shows diversion of the flow around the Campeche Bay Bump. It also shows another cyclonic gyre, in the northern Bay of Campeche centered at $\approx 22.5^\circ\text{N}$, 94°W , which is barely significant (Figures 3 and 4) but which is clearly seen in all the data (Figures 1 and 2).

The Mercator model is driven by real rather than climatic winds and is imbedded in an Atlantic Ocean model. While it and the float data also have other similarities (both indicate weaker flows in the northern and northwestern Gulf, as well as north of the Yucatan Peninsula) they do differ in the northwestern Gulf in that the model (as do most numerical models of the Gulf, e.g. *Oey et al.* 2005) shows an anticyclonic flow there while the data does not. In numerical models the northwestern Gulf is region where Loop Current rings are trapped and decay thereby creating a mean, anticyclonic flow there. This region of the Gulf was relatively, poorly sampled by the floats (Figure 1); however, an objective analysis we did which produced a non-divergent flow [*Gille*, 2003] did produce an anticyclonic gyre there (Plate 2).

We found the expected result that currents at intermediate depth were stronger when under the Loop Current or a warm-core Loop Current Ring. However, that we could find no consistent connection with the direction of intermediate depth flow and surface flow, as inferred from satellite altimeter maps, when under these features. We noted that many of the measurements were made on the lower continental rise where there are intermittent, energetic topographic Rossby waves. These waves are bottom intensified and we are unaware of them

having surface signatures. Perhaps these oscillations masked the connection at times. Also, some model results indicate that warm-core Loop Current rings may have cyclonic eddies beneath them [Welsh and Inoue, 2000] while others suggest that the lower layer flow under such features may uncouple from the upper layer flow and translate at a different rate [Lee and Mellor, 2003]. The observations reported indicate that the intermediate depth flow under these features is not related to them simply.

The above conclusions are supported by examining the floats' surface drifts. Figure 7 shows all the surface drifts averaged as for the intermediate depth drifts shown in Plate 2. Little connection between the surface and intermediate depth drifts is apparent when comparing Figure 7 and Plate 2. For example the surface flow is not southward along the western edge of the Gulf nor does it intensify in the western Bay of Campeche. There are exceptions though. A cyclonic gyre is found at the surface in the Bay of Campeche. It is also apparent that the intermediate depth drift tracks the Loop Current even as a portion of the latter deflects westward north of Cuba. When only the $n \geq 5$ values are plotted the cyclonic gyre in the Bay of Campeche survives (Figure 8). It appears also that the westward surface flow in the central Gulf in the region $23.5^\circ - 25.5^\circ \text{ N}$, $89^\circ - 91^\circ \text{ W}$ (Figure 8) counters the eastward intermediate-depth flow there (Figure 2). It is interesting that the one long-term moored average intermediate-depth current meter record from the same region indicates eastward flow too [Hamilton, this issue].

The float data indicate a mean cyclonic flow at intermediate depth around the northern and western edges of the Gulf of Mexico, which intensifies in the Bay of Campeche and diverts around the Campeche Bay Bump. The data also indicate little communication at intermediate depth between the eastern and western Gulf of Mexico. More data is needed to see if these inferences are artifacts resulting from limited spatial and temporal sampling or are indeed actual features of the intermediate depth flow in the Gulf of Mexico.

Acknowledgements. We thank D. Webb for helping us access and process the float data, R. Leben for providing us with satellite altimeter maps of the Gulf of Mexico, and R. Harkema for his data analysis. Support from Grant OSMFSU03 with Dynalysis of Princeton, Inc., from Grant 1435-01-00-CT-31105 with the Minerals Management Service, and support from a Secretary of the Navy Grant to J. O'Brien from the Office of Naval Research are gratefully acknowledged. Finally, we are grateful for the useful input and comments of the Gulf of Mexico researchers with whom we interacted during the course of this research.

Appendix for the issue's CD

Figures showing the intermediate depth velocities over consecutive 6-month periods starting in April 1998 and ending in March 2002. These figures were used for the results presented in the table in *Weatherly et al.* [this issue].

References

Blaha, J., G.H. Born, N.L. Guinasso, Jr., H.J. Herring, G.A. Jacobs, F.J. Kelly, R.R. Beden, R.D. Martin, Jr., G.L. Mellor, P.P. Niiler, M.R. Parks, R.C. Patchen, K. Shaudt, N. W. Scheffner, C.K. Shum, C. Ohlmann, W. Sturges III, G. L. Weatherly, D. Webb, and H.J. White, 2000: Gulf of Mexico Monitoring System, *Oceanography*, **13**, 10-17.

Brooks, D.A. and J.M. Bane, Jr. 1978: Gulf Stream deflection by a bottom feature off Charleston, *Science*, **201**, 1235-1226.

Chapman, P., S.F. DiMarco, R.E. Davis, and A.C. Coward, 2003: Flow at intermediate depths around Madagascar based on ALACE float trajectories. *Deep-Sea Res. II.*, **50**, 1957-1986.

Davis, R.E., 1998. Preliminary results from directly measuring mid-depth circulation in the tropical and South Pacific, *J. Geophys. Res.*, **103**, 24619-24639.

Davis, R. E., D. C. Webb, L. A. Regier, and J Dufour, 1992: The Autonomous Lagrangian Circulation Explorer (ALACE), *J. Atmos. Oceanic Technol.*, **9**, 264-284..

Davis, R.E., J.T. Sherman and J. Dufour, 2001: Profiling ALACEs and other advances in autonomous subsurface floats, *J. Atm. Oceanic Tech.*, **18**, 982-993.

Davis, R.E., 2004: Intermediate-depth circulation of the Indian and South Pacific Oceans measured by autonomous floats, submitted to *Deep-Sea Res.*

DeHaan, C.J., 2003: Determining the deep current structure in the Gulf of Mexico, Ph.D. Thesis, Dept. of Oceanography, Florida St. Univ., Tallahassee, FL 80 pp.

Dimarco, S. F., W. D. Nowlin, and R. O. Reid, 2005. A statistical description of the near-surface

velocity field from drifters in the Gulf of Mexico, this issue.

Emery, W.K. and R.E. Thomson, 2001: **Data analysis methods in physical oceanography**, Elsevier, Amsterdam, 658 pp.

Fischer, J. and F. A. Schott, 2002: Labrador Sea Water tracked by profiling floats – from the boundary current into the open Atlantic, *J. Phys. Oceanogr.*, **32**, 573-584.

Gille, S.T., 2003: Float observations of the Southern Ocean. Part I. Estimating mean fields, bottom velocities, and topographic steering, *J. Phys. Oceanogr.*, **33**, 1167-1181.

Groupement Mercator Ocean.<http://www.Mercator-ocean.com.fr/en>

Hamilton, P. 1990: Deep currents in the Gulf of Mexico, 1990: *J. Phys. Oceanogr.*, **20**, 167-181.

Hamilton, P. 2005: A Note on Deep Mean Currents in the Gulf of Mexico Obtained from moorings, this issue.

Hamilton, P. and L. Lugo-Fernandez, 2001: Observations of high-speed currents in the northern Gulf of Mexico, *J. Geophys. Res.*, **97**, 2185-2200.

Johnson, G. C., P. J. Stabeno and S. C. Riser, 2004: The Bering Slope Current System Revisited, *J. Phys. Oceanogr.*, **34**, 384–398

Kwon, Y.-O., and S.C. Riser, 2005: The General Circulation of the Western Subtropical North Atlantic Observed Using Profiling Floats. Submitted to *J. Geophys. Res.*.

Lavender, K., R.E. Davis and B. Owens, 2000.: Mid-depth recirculation observed in the interior Labrador and Irminger Seas by direct velocity measurements, *Nature*, **407**, (7 Sept.), 66-69.

Lee, H.-C. and G.L. Mellor, 2003: Numerical simulation of the Gulf Stream System: the Loop Current and the deep circulation, *J. Geophys. Res.*, **108** (C2) 10.1029/2000JC000736,

Oey, L.-Y. and H.-C. Lee, 2003: Deep eddy energy and topographic Rossby waves in the Gulf of Mexico, *J. Phys. Oceanogr.*, **32**, 3499-3527.

Oey, L.-C., T. Ezer, and H.-C. Lee, 2005: Loop Current, rings, and related circulation in the Gulf of Mexico: a review of numerical models and future challenges, this issue.

Ohshima, K. I., D. Simizu, M. Itoh, G. Mizuta, Y. Fukamachi, S. C. Riser and M. Wakatsuchi, 2004: Sverdrup Balance and the Cyclonic Gyre in the Sea of Okhotsk. *J. Phys. Oceanogr.*, **33**, 3499-3527, 513–525.

Owens, W.B., 1991: A statistical description of the mean circulation and eddy variability in the northwestern Atlantic using SOFAR floats, *Prog. Oceanogr.*, **28**, 257-303.

Richardson, P.L. and S.L. Garzoli, 2003: Characteristics of intermediate water flow in the Benguela Current as measured by RAFOS floats, *Deep-Sea Res. II*, **50**, 87-118.

Schmitz, W.J., Jr, 2005. Cyclones and westward propagation of in the shedding of anticyclonic rings from the Loop Current, this issue.

Vazquez de la Cerda, A.M, 1993: Bay of Campeche Cyclone, Ph.D. Dissertation, Dept. of Oceanography, Texas A.& M. Univ., College St., Texas, 91 pp.

Vazquez de la Cerda, A. M. , R. O. Reid, S. F. DiMarco, and A. E. Jochens, 2005; Bay of Campeche: an update, this issue.

Weatherly, G., N. Wienders and R. Harkema, 2003. Temperature inversions in the open Gulf of Mexico, *J. Geophys. Res.*, **108**, (C6) 10.1029/2002JC001680.

Weatherly, G.L., 2004 Intermediate depth circulation in the Gulf of Mexico: PALACE Float Results between April 19988 and March 2002, U.S. Dept. of the Interior, Minerals Management Service, New Orleans, LA, 41 pp, available at <http://www.gomr.mms.gov/homepa/regulate/environ/studies/2004/2004-13.pdf>.

Welsh, S.E., 1996: A numerical modeling study of the Gulf of Mexico under present and past environmental conditions, Ph.D. Dissertation, Louisiana St. Univ., Baton Rouge, Louisiana, 206 pp.

Welsh, S.E. and M. Inoue, 2000: Loop current rings and deep circulation in the Gulf of Mexico, *J. Geophys. Res.*, **105**, 1,951-16,959.

Period	Cyclonic flow along slope					Campeche Bay Gyre
	(a)	(a)	(a)	(a)	(a)	
	NE	N	NW	WCB	CBB	
04/98≤time<10/98	x	x	x			
10/98≤time<04/99	x	x	x	x	x	x
04/99≤time<10/99		x	x	x	x	x
10/99≤time<04/00		x	x	x	x	x
04/00≤time<10/00		x	x	x	x	
10/00≤time<04/01	x	x	x		x	x
04/01≤time<10/01	x	x	x	x		x
10/01≤time<04/02		x	x		x	

Table. A tabulation, using the velocities presented in Figures A1-A8 in this issue's CD (also shown in [Weatherly, 2004]), of when different regions along the edge of the Gulf of Mexico had their intermediate depth flow measured. Under (a) NE is the region in the northeast Gulf of Mexico east of 89°W, N is the region in the northern Gulf of Mexico between 89°W and 95°, NW is the western Gulf of Mexico north of 23°N, WCB is the western Gulf of Mexico in Bay of Campeche, and CBB is the Campeche Bay Bump. Under (b) is the cyclonic, gyre in the western Bay of Campeche centered near 20.5°N, 95.5°W.

Figure Captions.

Figure 1. The 900-dbar velocities estimated from the intermediate-depth drifts. The vectors mid-points are centered at the mid-point of the intermediated-depth drifts. The black (grey) vectors are from floats launched west (east) of 89°W. The 900-m and 2000-m isobaths are shown.

Figure 2. Plate 2's data (blue vectors) redrawn including only those averages formed when the number ≥ 5 .

Figure 3. The same as Figure 2 but with uncertainty ellipses and values shown every $1/2^\circ$ latitude by every $1/2^\circ$ longitude rather than every $1/4^\circ$ latitude by every $1/4^\circ$ longitude.

Figure 4. All the temperature profiles from a 1° latitude by 1° longitude bin centered at 26.5°N , 89.0°W . The right-most profile was made in a warm-core Loop Current ring.

Figure 5. Histograms of the intermediate-depth velocity magnitude of all the measurements (solid line) and only those measurements estimated to be made under the Loop Current or a warm-core Loop Current ring (dashed line).

Figure 6. Average flow at 1000 m depth for the year 2000 computed by the Mercator model.

Figure 7. Like Plate 2 except the surface velocity replaces the intermediate-depth flow and no objective analysis.

Figure 8. Like Figure 2 except the surface velocity.

Plate 1. Estimates of the surface drifts (yellow and blue) and subsurface drifts (black). The blue (yellow) drifts are from floats launched east (west) of 89°W . The (black) intermediate-depth drifts are seaward of the 900 m isobath.

Plate 2. The average intermediate-depth velocity in $1/2^\circ$ latitude by $1/2^\circ$ longitude bins (blue vectors). The vectors are centered at the mid-point of the bins. Values are shown for bins centered every for $1/4^\circ$ latitude by every $1/4^\circ$ longitude. The red vectors are the objective analysis inferred velocities formed from the blue vectors by a scheme which is horizontally non-divergent (see text). The 900-m isobath is shown.

Plate 1. Estimates of the surface drifts (yellow and blue) and subsurface drifts (black). The blue (yellow) drifts are from floats launched east (west) of 89°W. The (black) intermediate-depth drifts are seaward of the 900 m isobath.

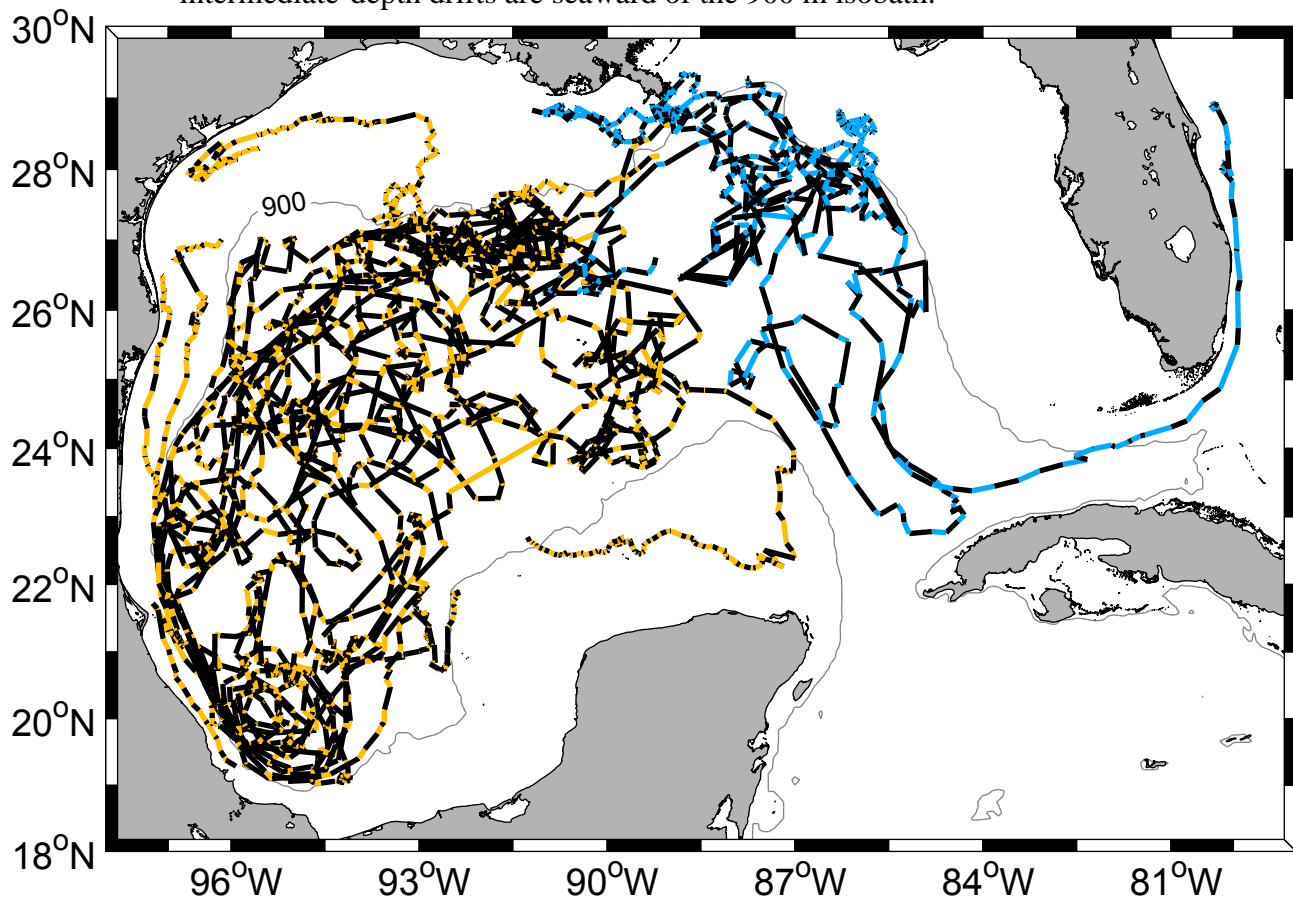


Figure 1. The 900-dbar velocities estimated from the intermediate depth drifts. Vectors are centered at the mid-point of the drifts. The black (gray) vectors were launched west (east) of 89W. The 900-m and 2000-m isobaaths are shown.

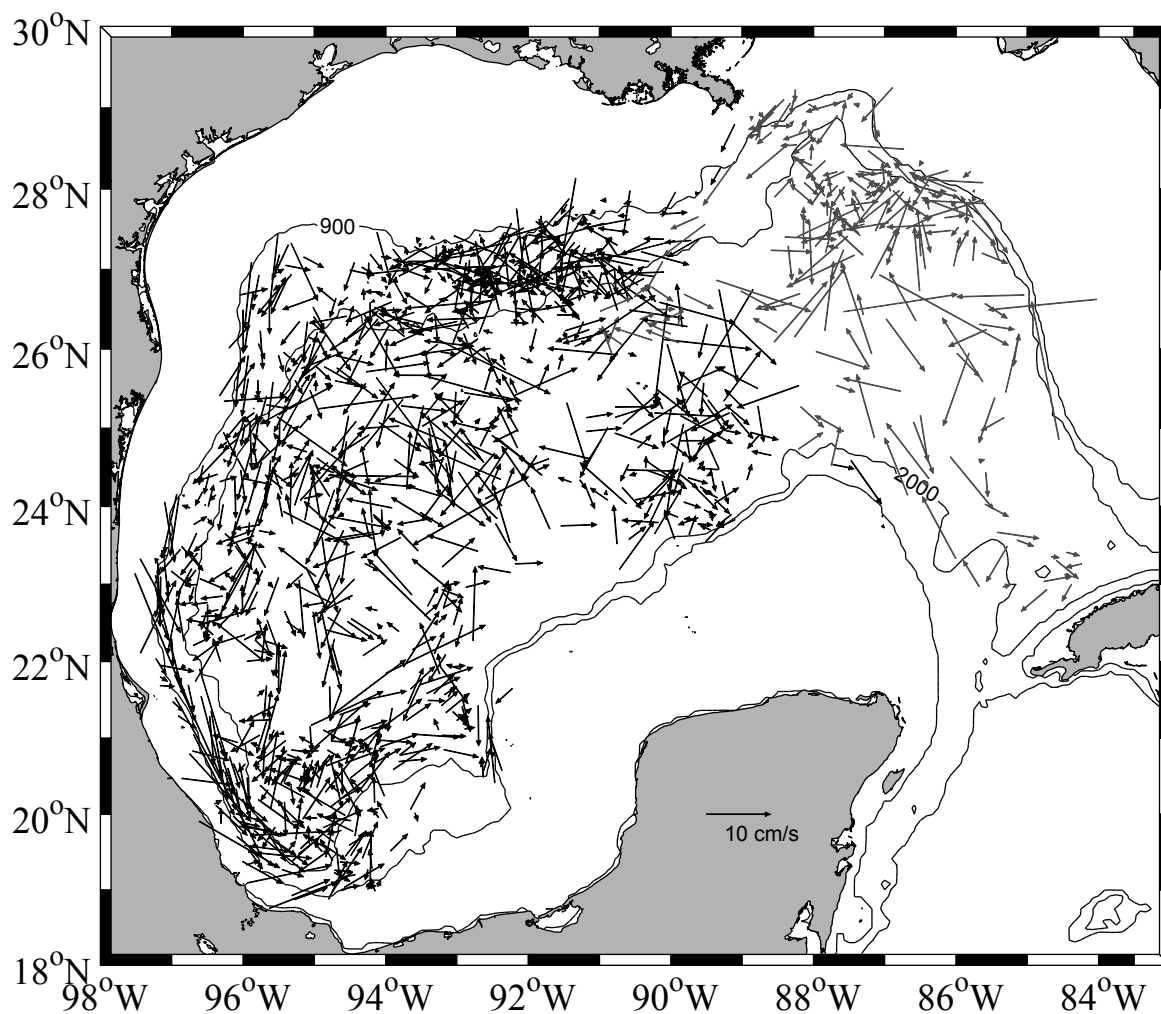


Plate 2. The average intermediate-depth velocity in $1/2^\circ$ latitude by $1/2^\circ$ longitude bins (blue vectors). The vectors are centered at the mid-point of the bins. Values are shown for bins centered every $1/4^\circ$ latitude by every $1/4^\circ$ longitude. The red vectors are the objective analysis inferred velocities formed from the blue vectors by a scheme which is horizontally non-divergent (see text). The 900-m isobath is shown.

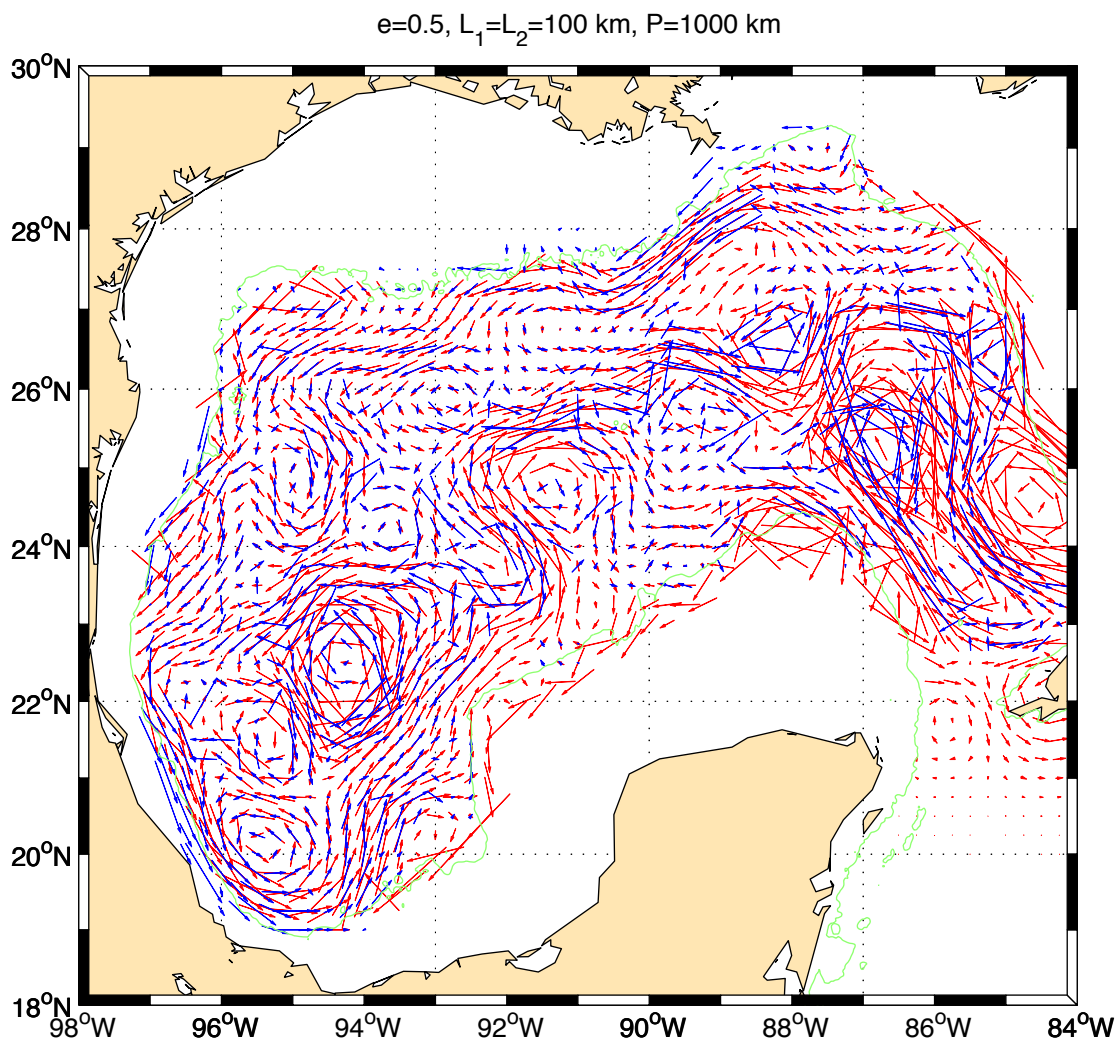


Figure 2. Plate 2's data (blue vectors) redrawn including only those averages formed when the number > 4 . 900-m isobath is shown.

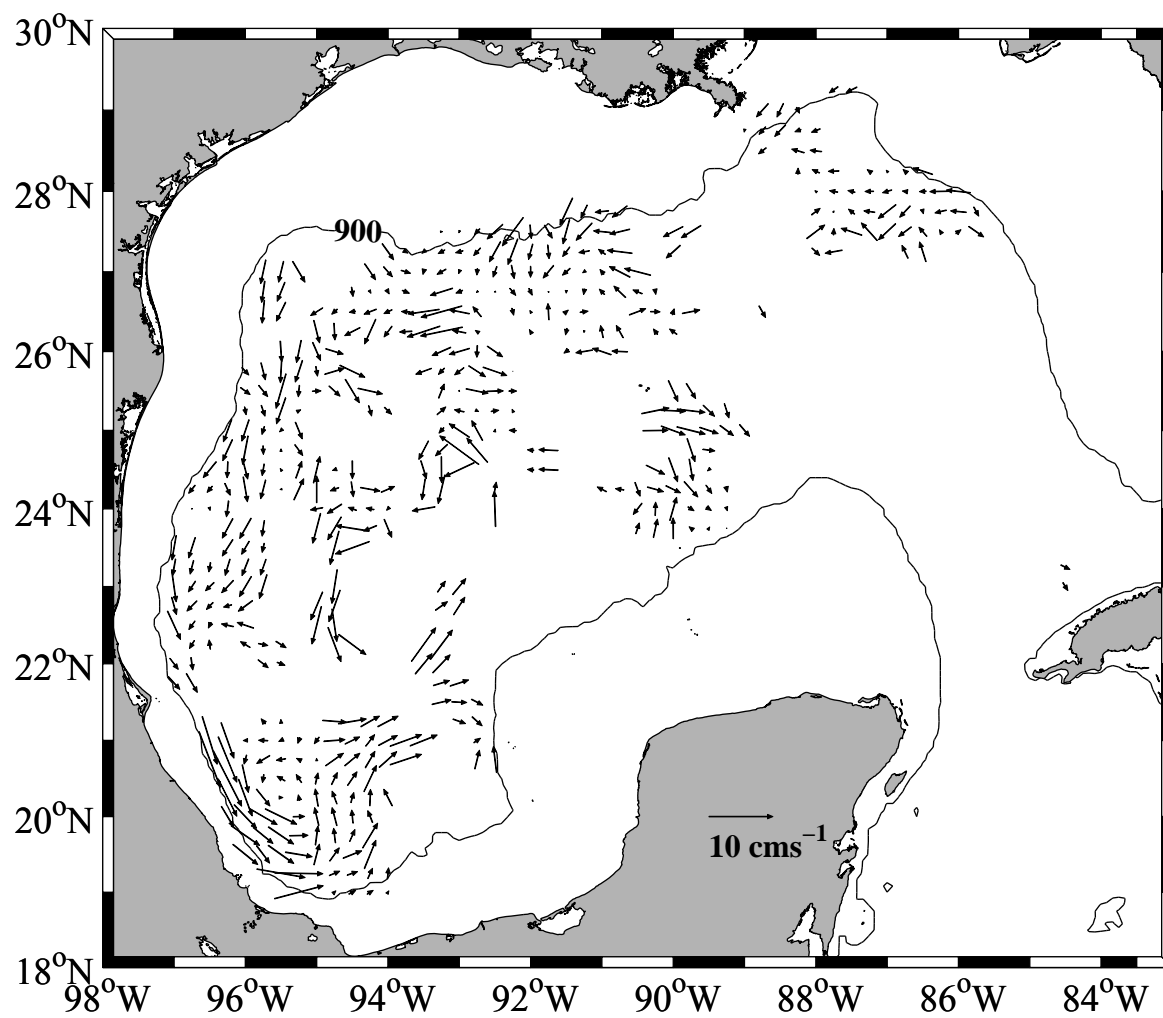


Figure 3. The same as Figure 2 except with uncertainty ellipses and values shown every 1/2 deg latitude by 1/2 deg longitude.

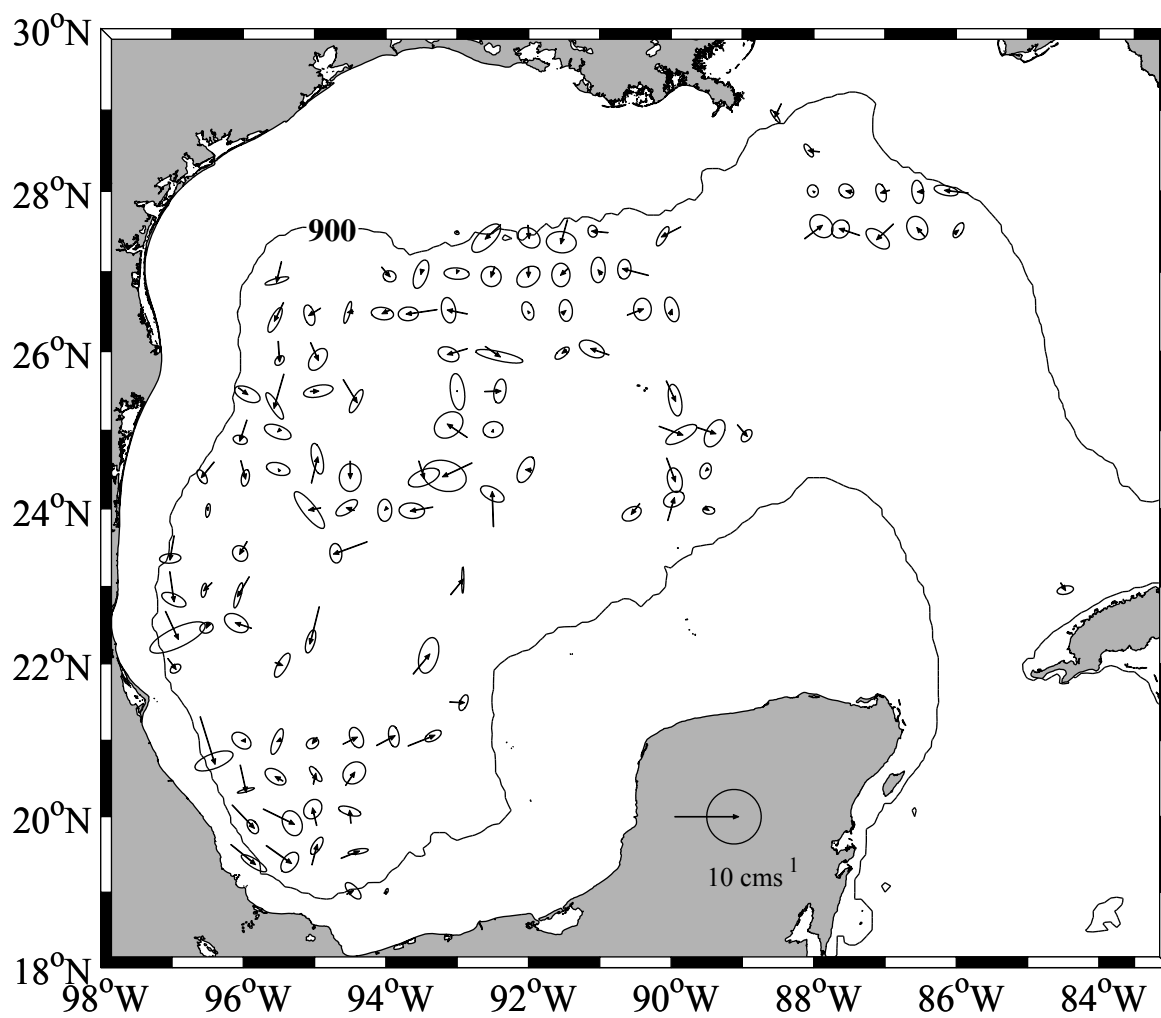


Figure 4. All the pemperature profiles from a 1 deg lat. by 1 deg long. bin centered at 26.5 N, 89.0 W. The right-most is from a warm-core ring.

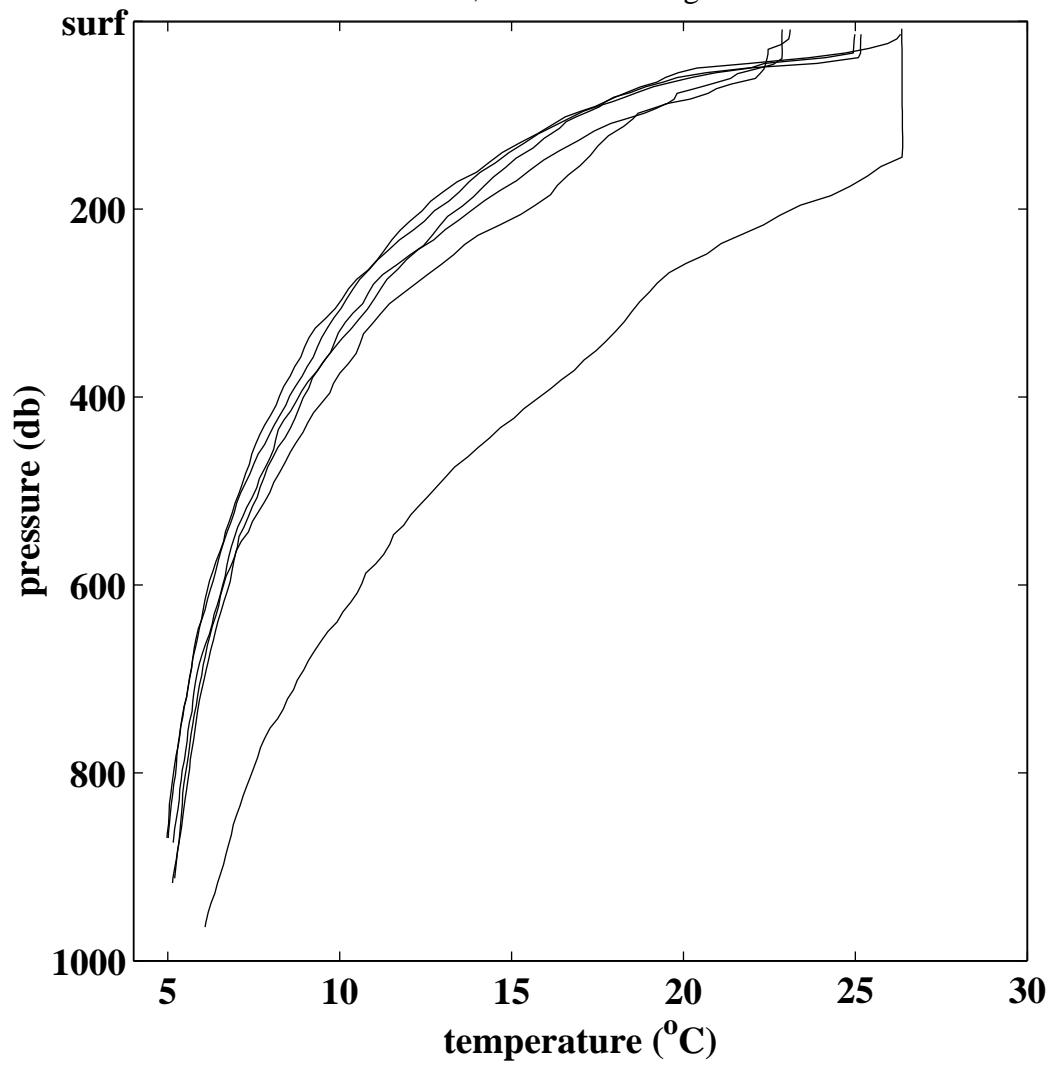


Figure 5. Histograms of the intermediate-depth velocity magnitude of all the measurements (solid line) and only those estimated to be under the Loop Current or a warm-core Loop Current ring (dashed line).

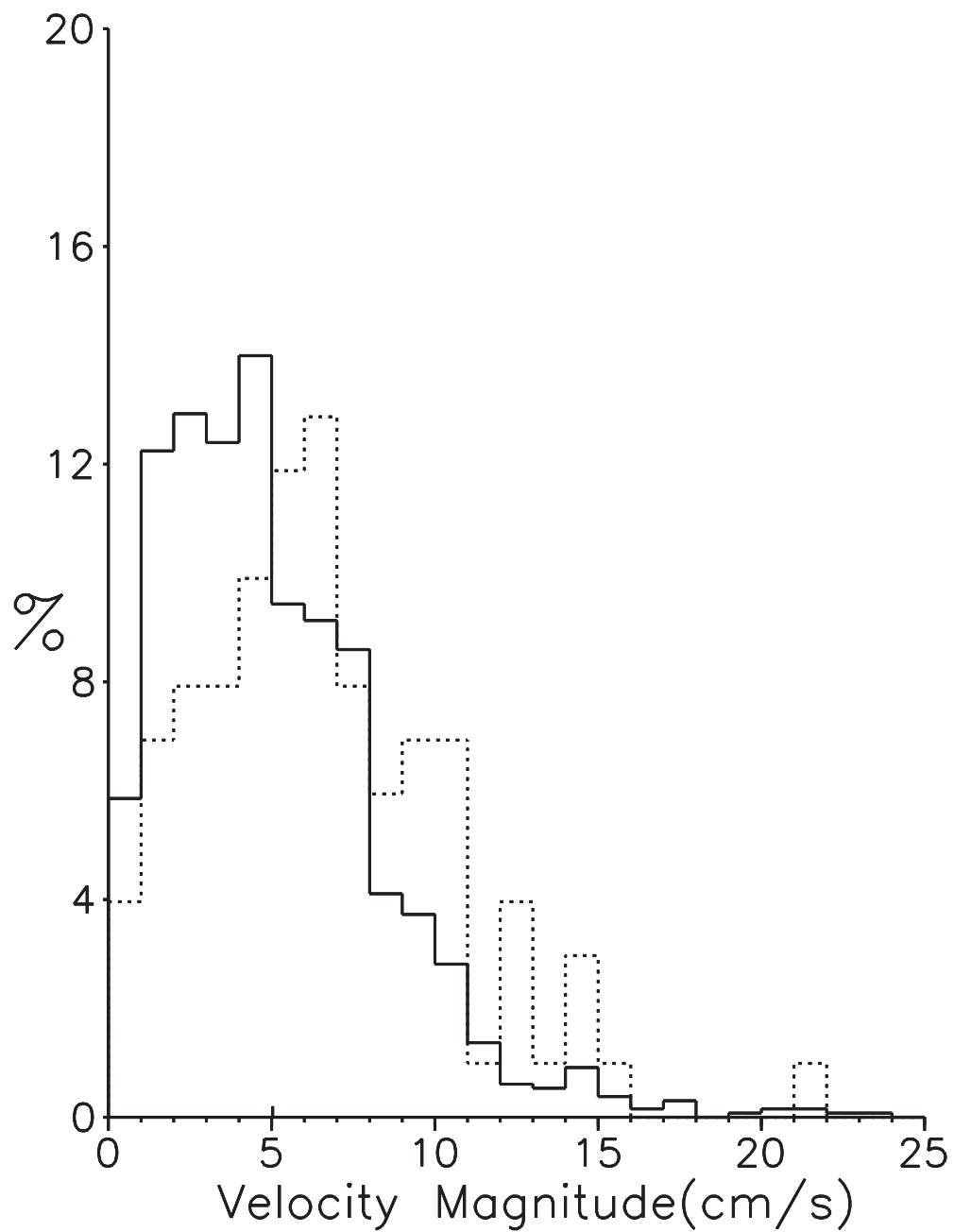


Figure 6. Average flow at 1000 m depth for the year 2000 computed by the Mercator model.

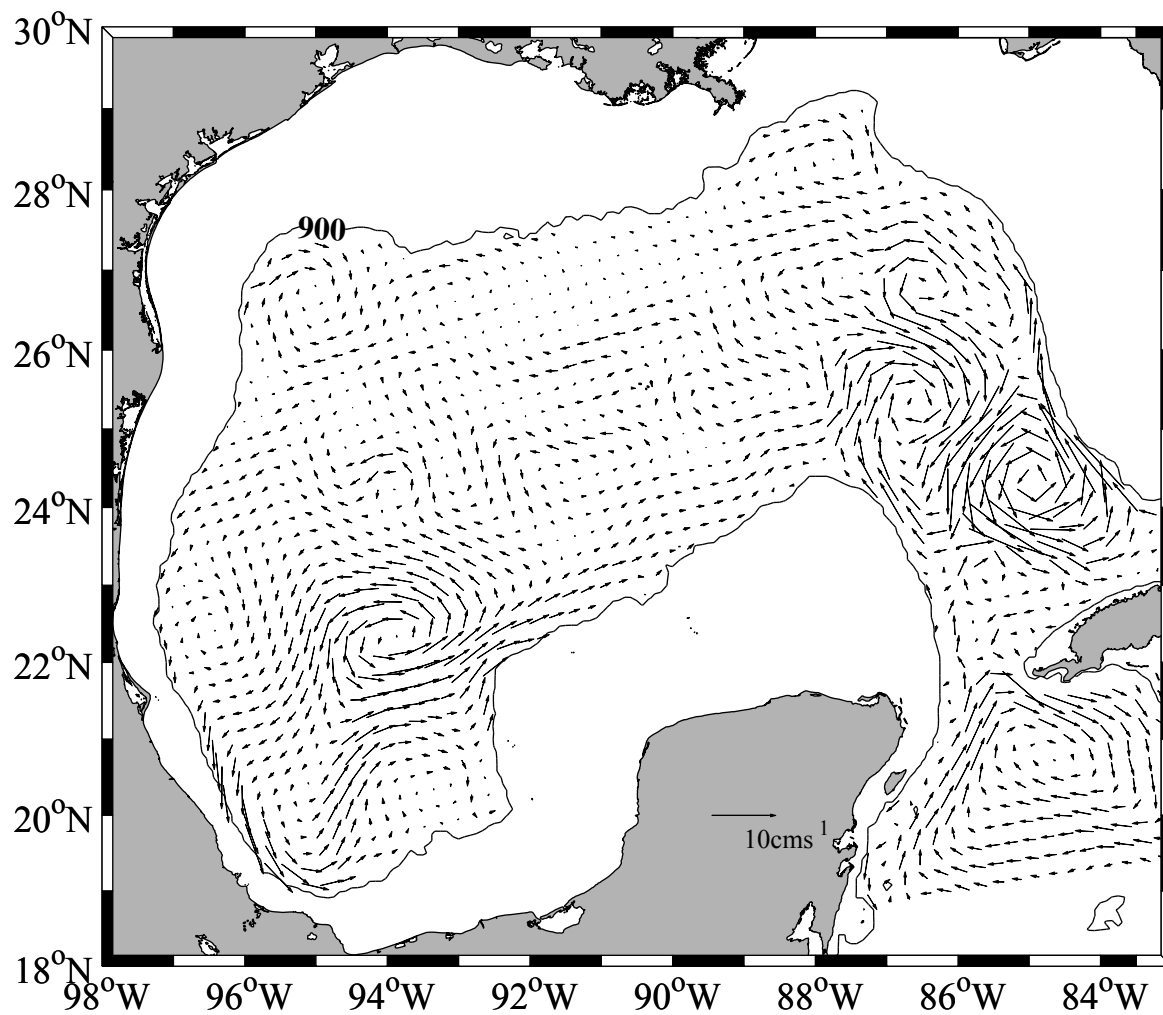


Figure 7. Like Plate 2 except the average surface velocity replacing the intermediate depth flow and no objective analysis.

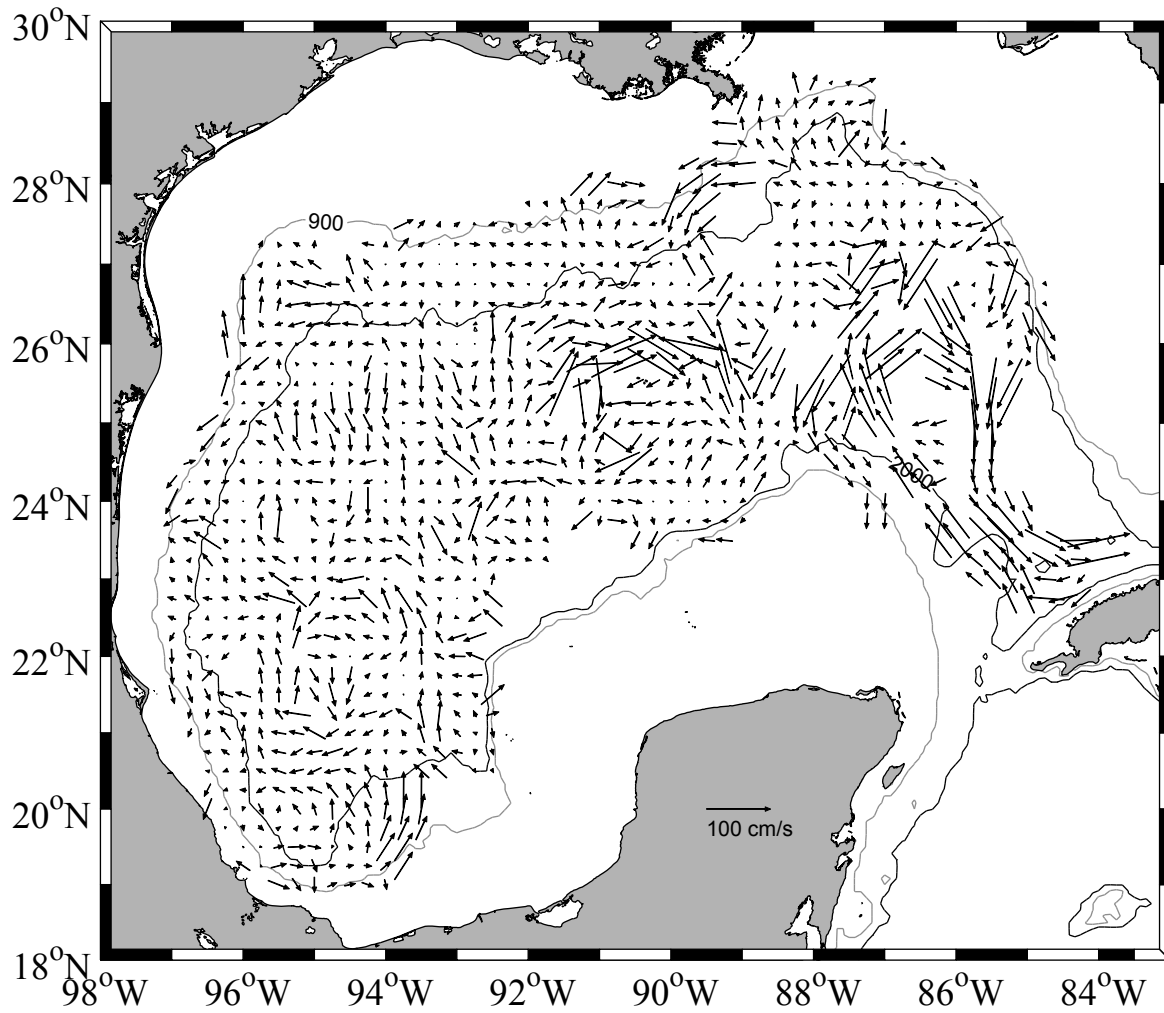


Figure 8. Like Figure 2 except the surface velocity.

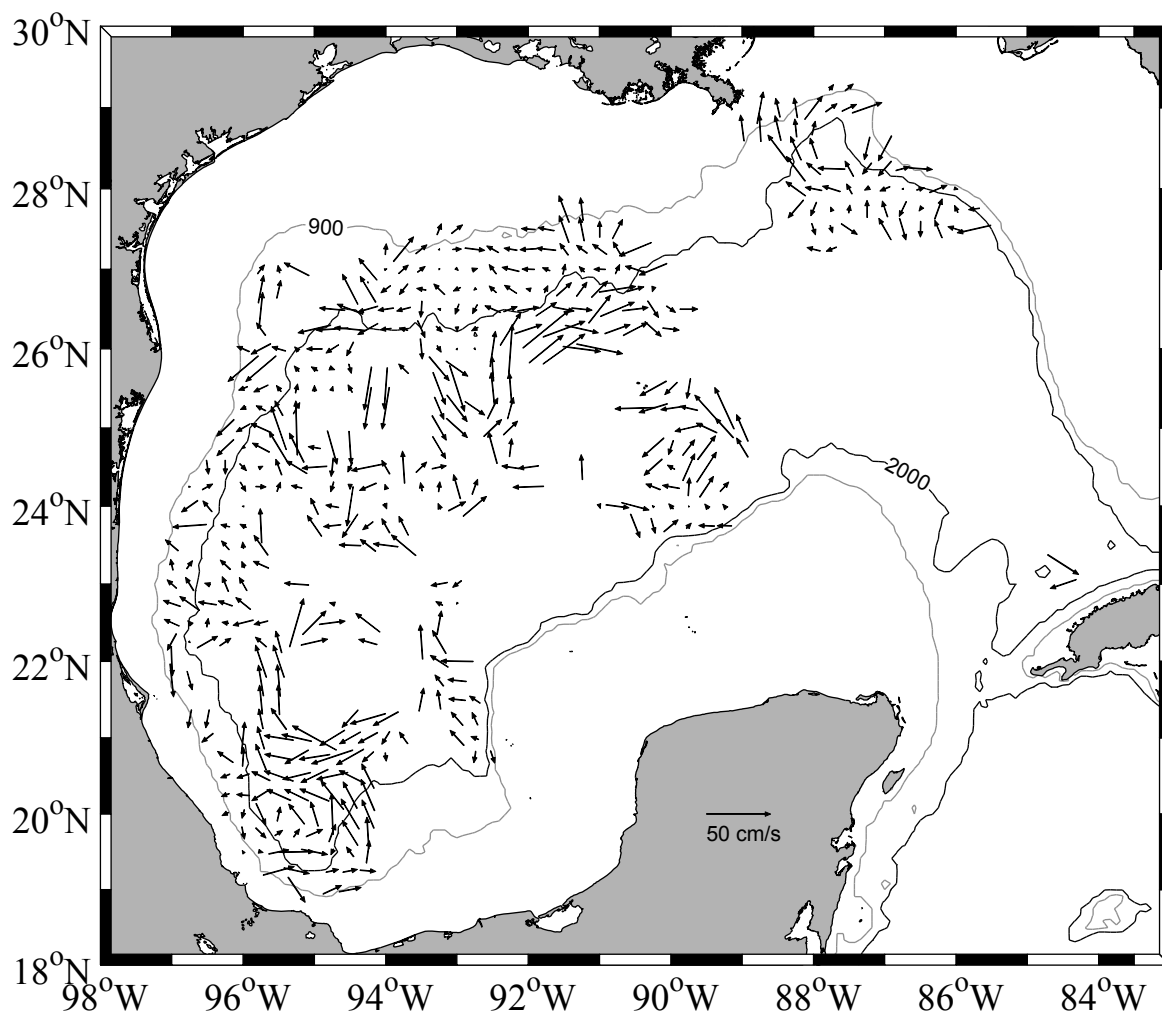


Figure A1

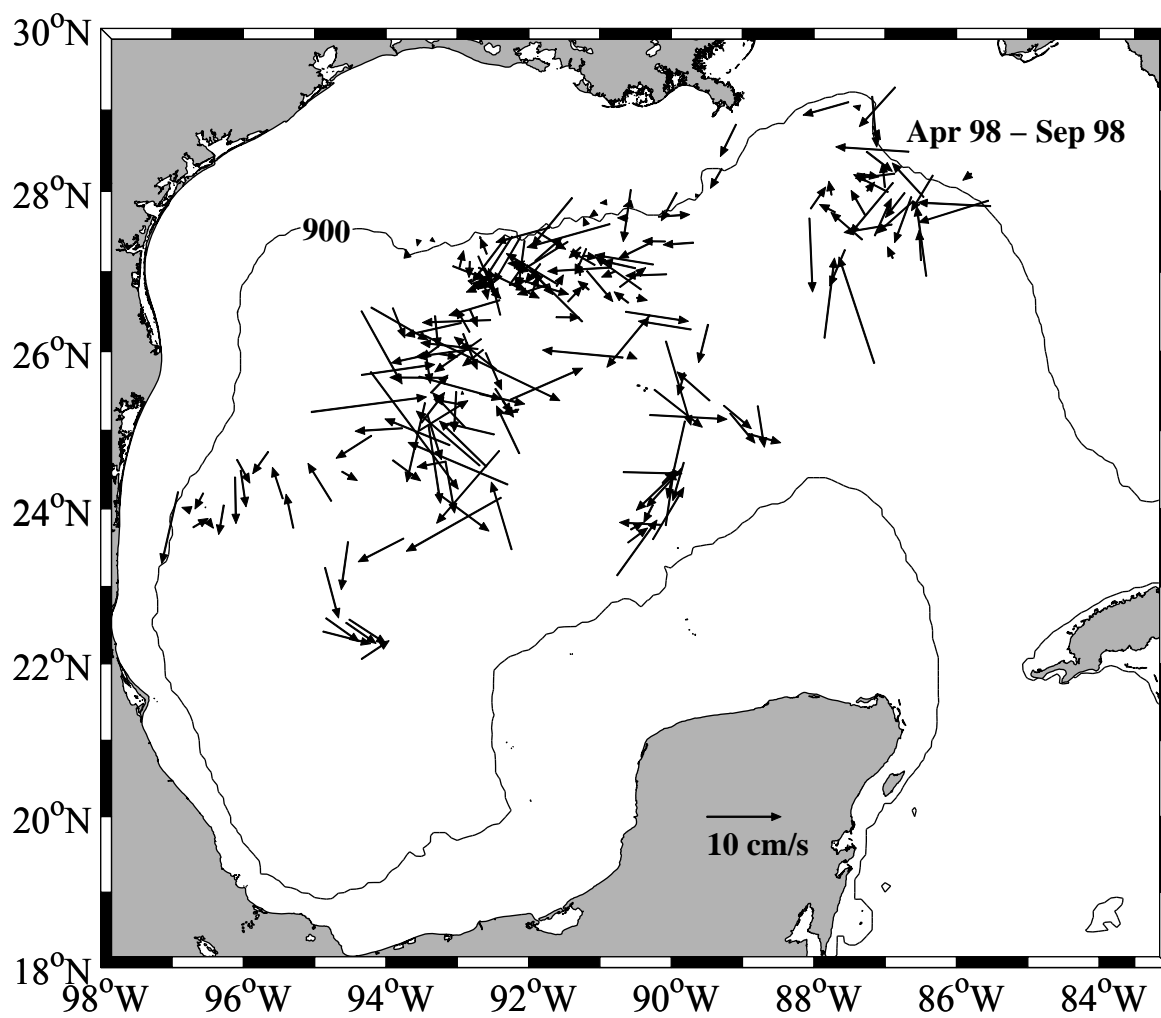


Figure A2

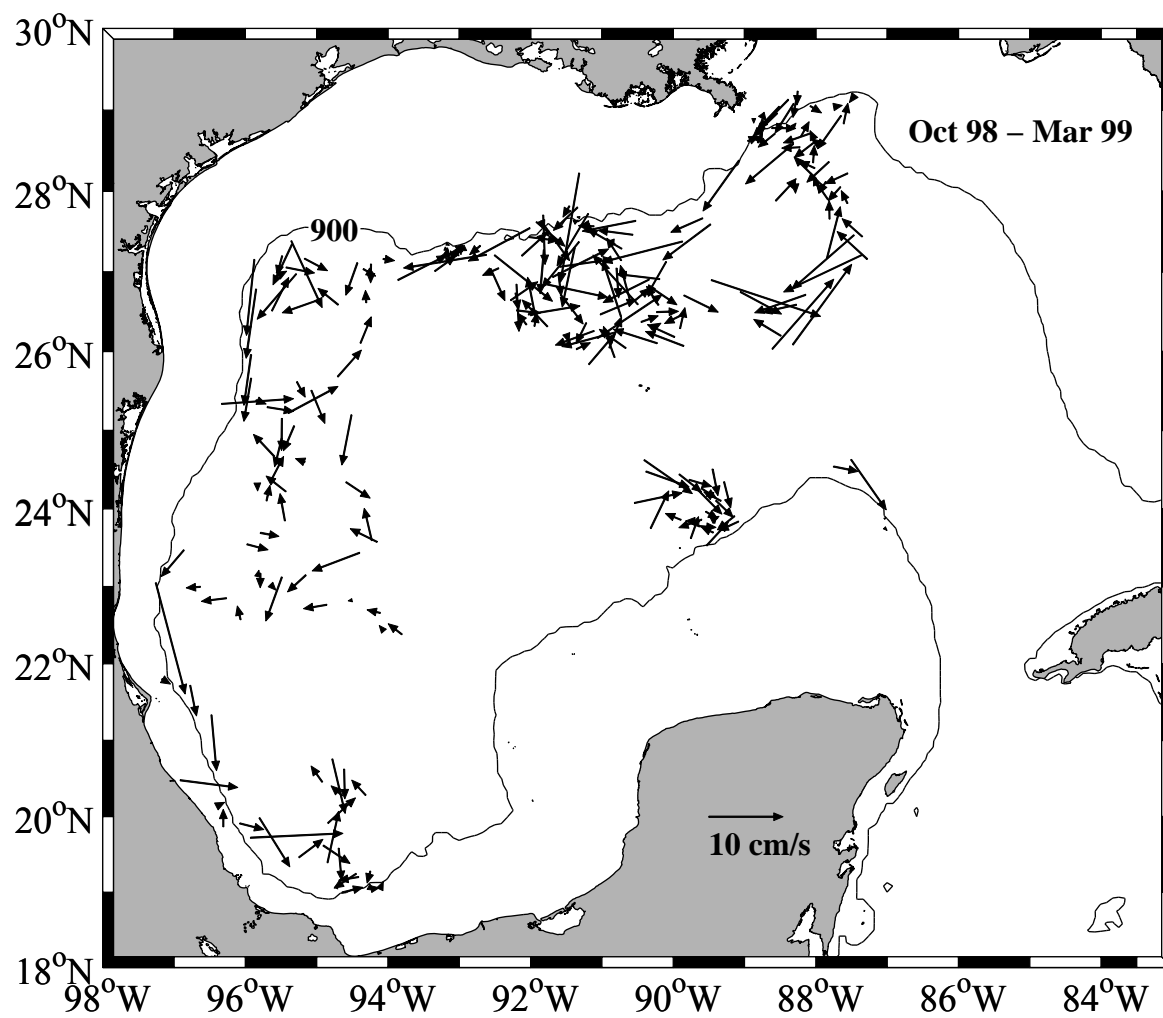


Figure A3

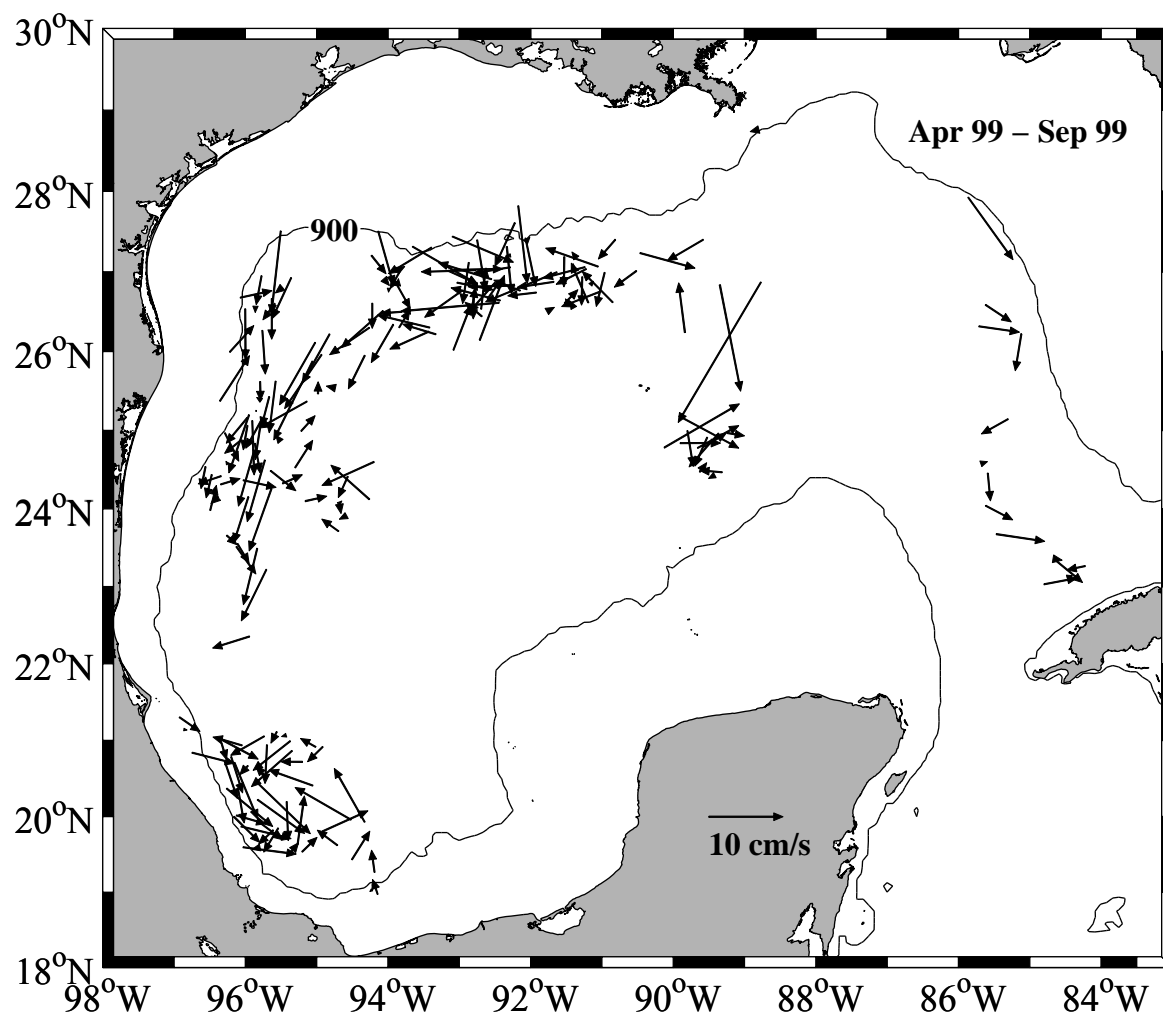


Figure A4

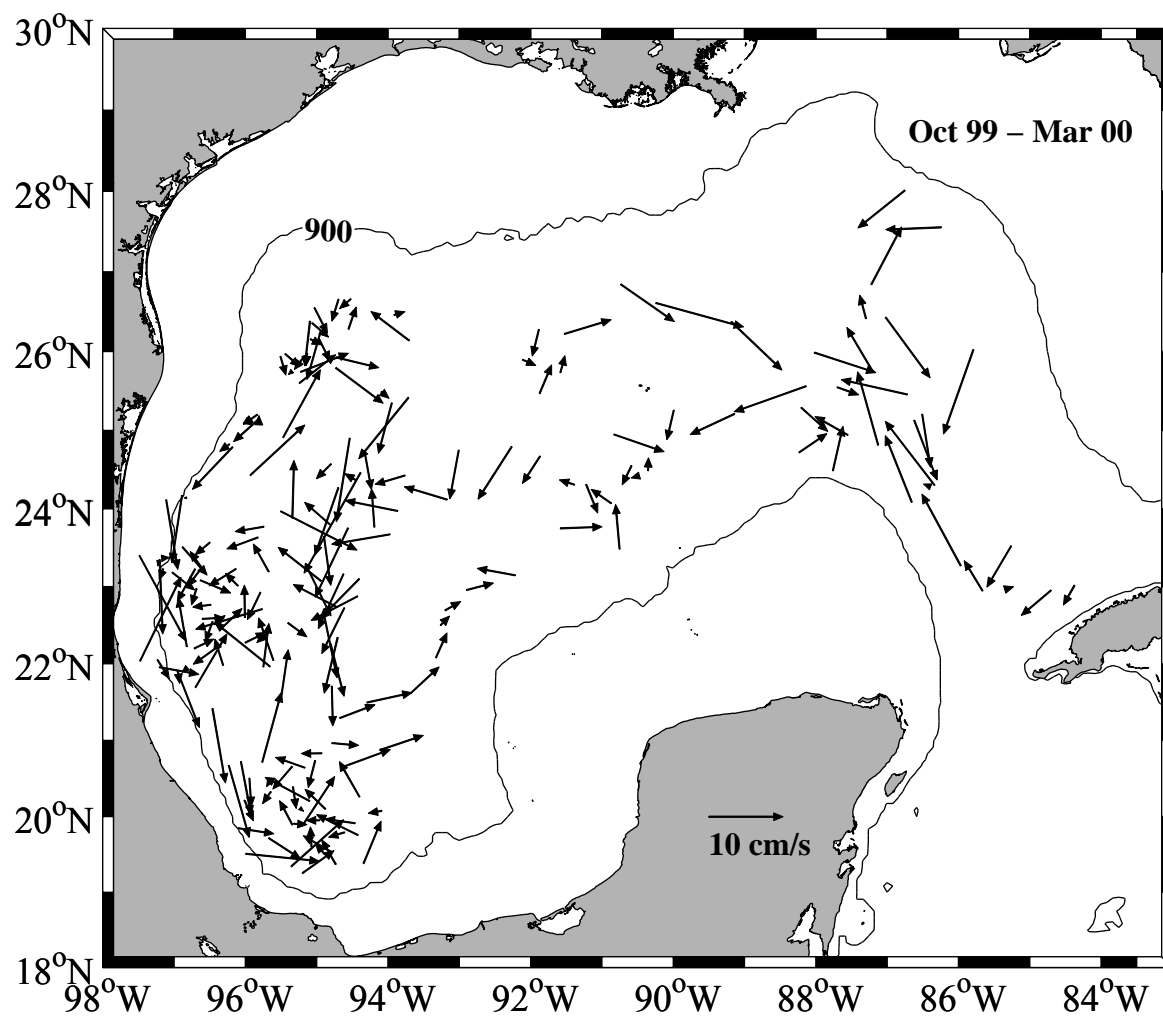


Figure A5

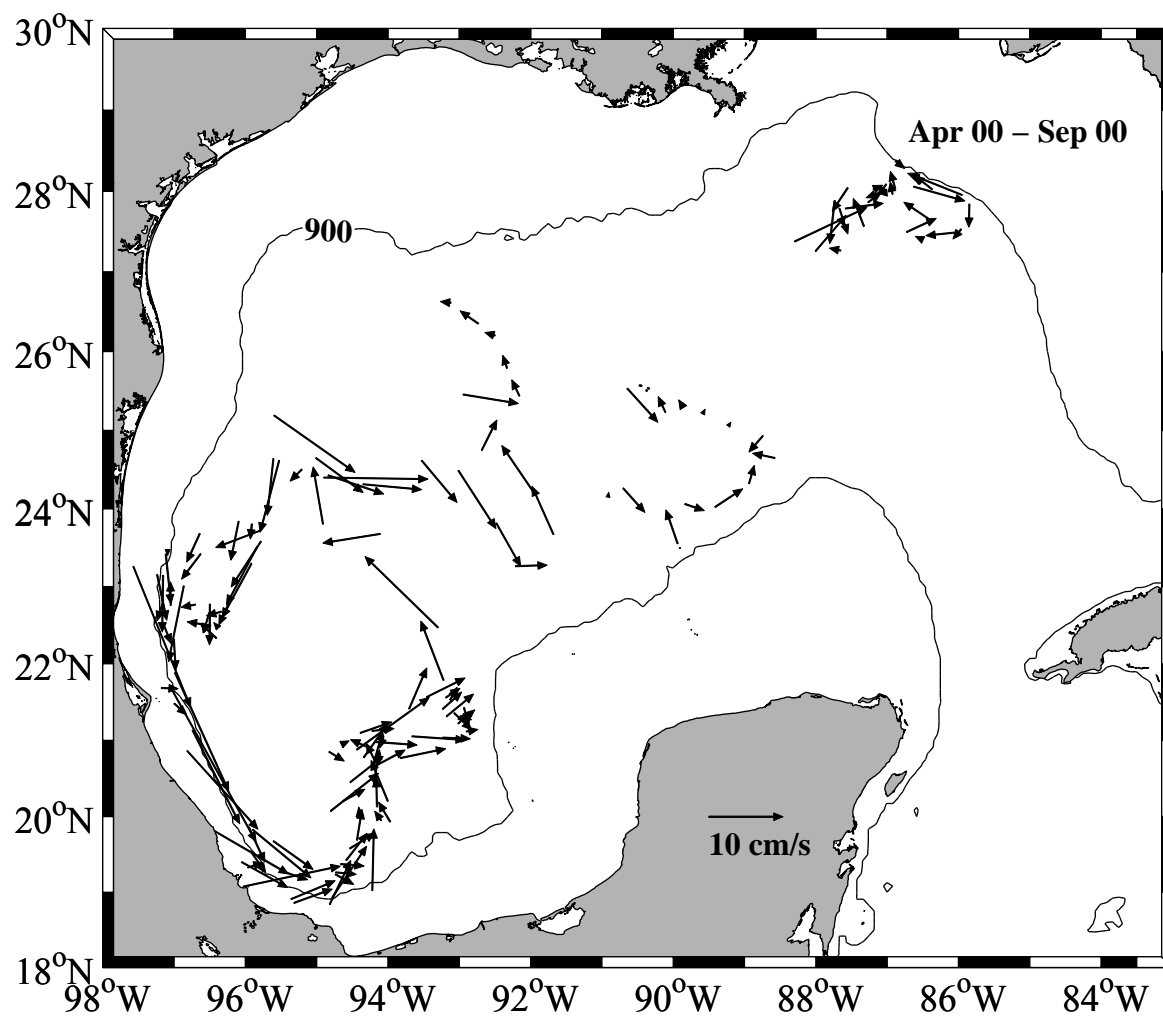


Figure A6

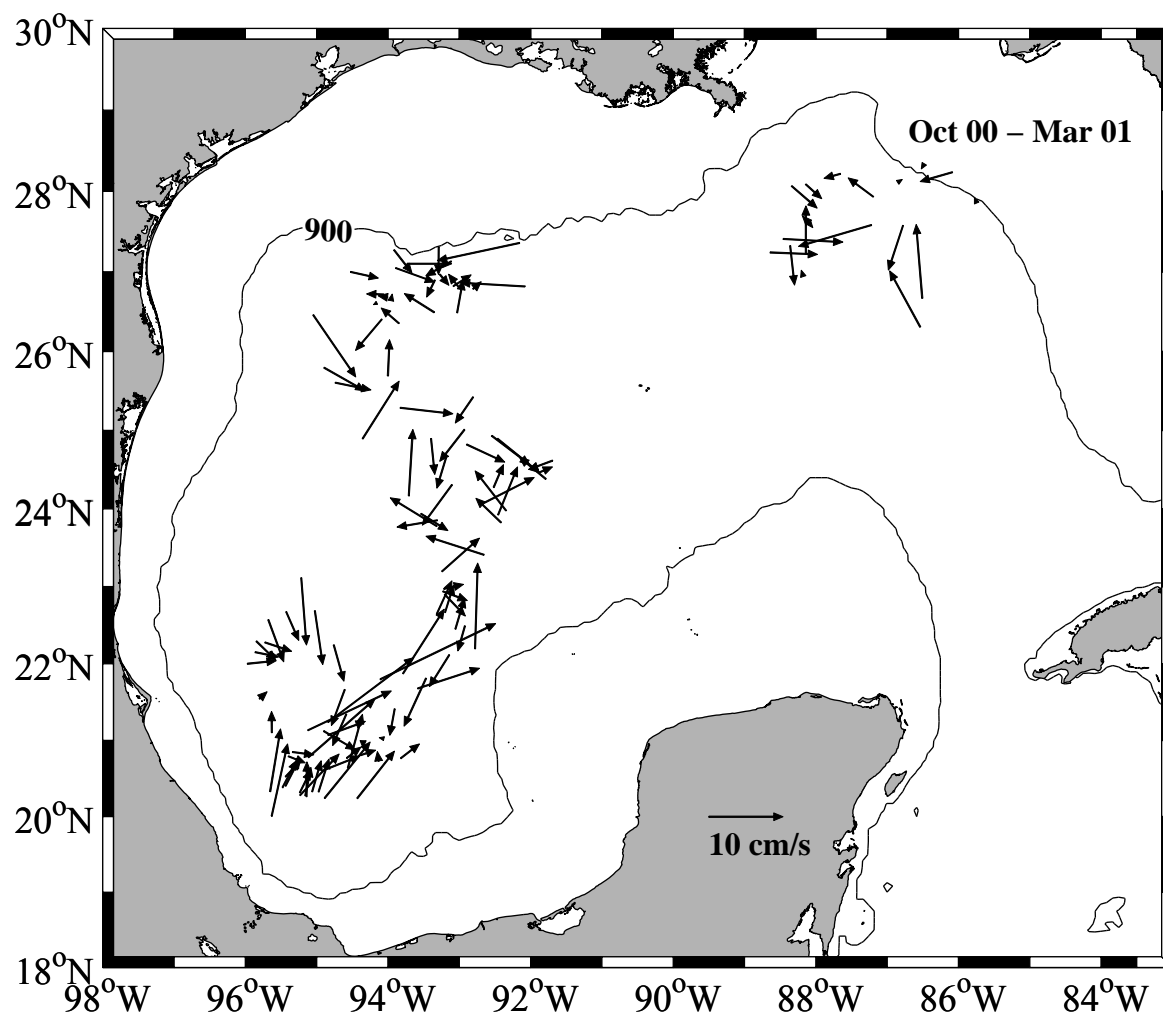


Figure A7

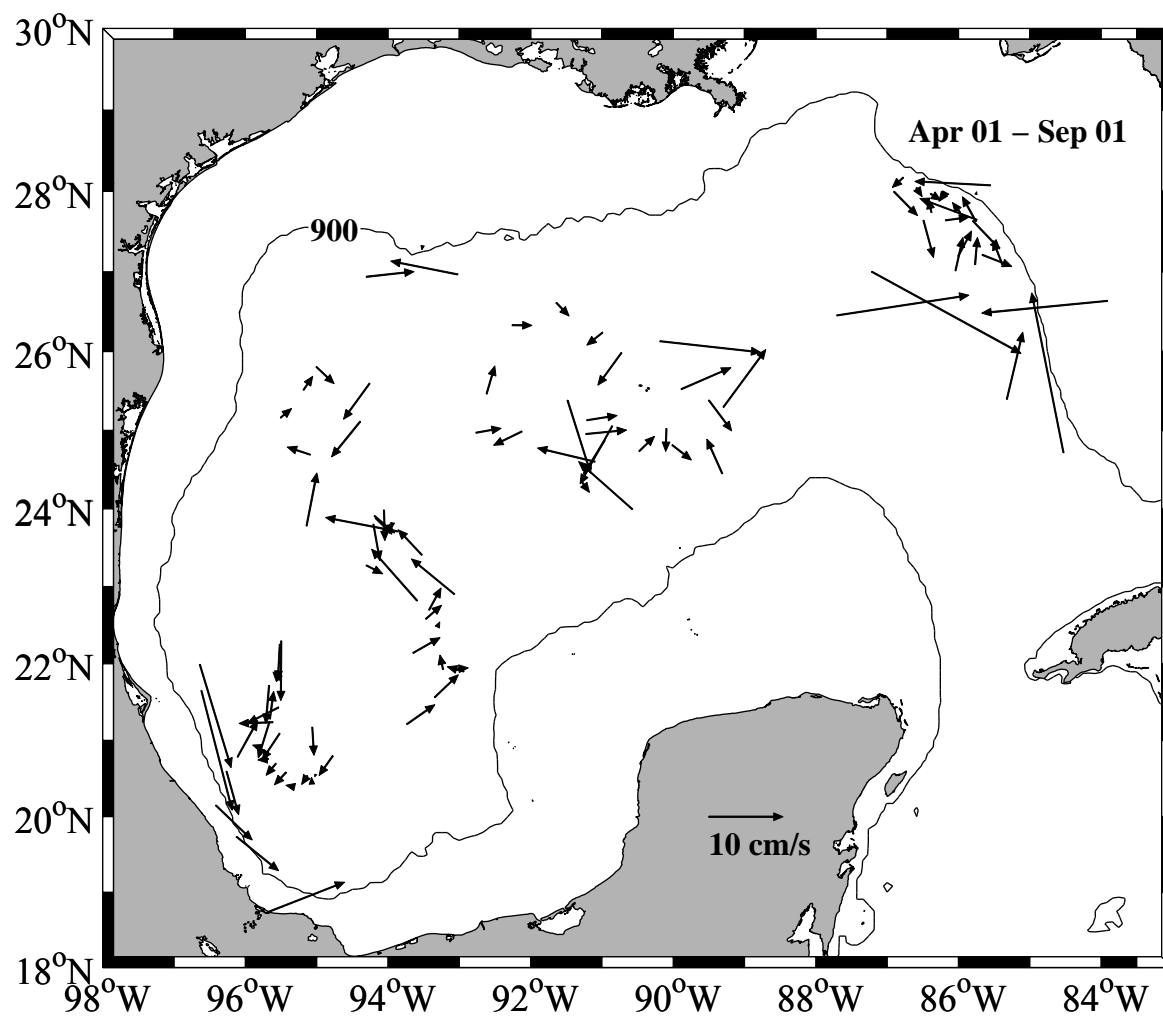


Figure A8

